The correctness to the spuriously simulated semi-annual cycle of the sea surface temperature in the equatorial eastern Pacific

Song Zhenya[1], Qiao Fangli[1*] & Wang Chunzai[2]
[1]The First Institute of Oceanography, State Oceanic Administration, Qingdao, China
[2]NOAA Atlantic Oceanographic and Meteorological Laboratory, USA

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Abstract

One of the challenges faced by the climate model of the Community Climate System Model version 3 (CCSM3) is the spuriously simulated semi-annual cycle of the sea surface temperature (SST) in the equatorial eastern Pacific. This model bias has limited the performance of the climate simulation and prediction. Based on the surface wave-circulation coupled theory, an atmosphere-wave-ocean coupled model was developed, which incorporates the MASNUM (Marine Sciences and Numerical Modeling) wave number spectral model into CCSM3. The new coupled atmosphere-wave-ocean model successfully removes the spurious semi-annual cycle simulated by the original CCSM3 and reasonably produces an SST annual cycle with warm and cold phases in April and August, respectively. The correlation between the simulated and observed SST in the equatorial eastern Pacific is improved from 0.66 to 0.93. The ocean surface layer heat budget analysis indicates that the wave-induced vertical mixing is responsible for improving the simulation of the SST seasonal cycle in the equatorial eastern Pacific.

Key Words: **SST seasonal cycle; the eastern Pacific; the wave-induced mixing; CGCMs**

1. Introduction

The equatorial eastern Pacific, which is with persistent ocean heat gain and involves air-sea interaction, is a key region for ENSO variability and even for global climate. The equatorial eastern Pacific exhibits a pronounced annual cycle in sea surface temperature (SST) in spite of the dominance of the semi-annual cycle in solar radiation (Fig. 1). In addition, the March-April warm phase and August-October cold phase occur when the semi-annual solar forcing is at its maxima [1, 2]. Much effort has been paid to investigate the reasons why SST shows annual cycle [1-4]. Many physical processes both in the ocean and atmosphere and coupled feedback processes have been hypothesized to contribute to the generation of the annual cycle in the equatorial eastern Pacific. Since it involves complex dynamical and physical interaction among the climate subsystems, the annual cycle of SST in the equatorial eastern Pacific can be served as an indicator for testing the performance of the coupled general circulation models (CGCMs).

CGCMs have problems for simulating the seasonal SST cycle in the equatorial eastern Pacific [3, 5-6]. *De Szoeke et al*. (2008) compared the results of 15 CGCMs submitted to the Program for Climate Model Diagnosis and Inter-comparison (PCMDI) and showed that most of these 15 models simulate two cold phases in the equatorial eastern Pacific SST rather than a single cold phase as observed [7]. For example, the simulation of the Community Climate System Model version 3 (CCSM3) has a quite strong semi-annual SST cycle in the equatorial eastern Pacific, which is regarded as one of six challenges for further development of CCSM [8-9]. This model bias is particularly evident in region of 5°N-5°S and 110°W-90°W, with two cold phases in February and August, and two warm phases in May and December (Fig 2, the solid line).

The causes for this model bias in CCSM3 are not well understood yet. The effects by increasing the model spatial resolution are not obvious for reducing this bias [9]. It has been suggested that the amount of low-level stratus clouds, the land surface process, and the ocean mixing and upwelling may be factors influencing the simulation of the annual cycle [5]. *Large and Danabasoglu* (2006) pointed out that ocean general circulation models (OGCMs) can simulate the annual cycle more properly in the equatorial eastern Pacific than the CGCMs [9]. Certain model biases that develop in a coupled model could be amplified by the air-sea feedback.

Surface gravity waves, as the most energetic motion in the upper ocean, should play an important role in the upper ocean. Instead of considering the wave breaking effect, the wave-motion-induced vertical mixing (hereafter wave-induced mixing), Bv, is expressed as the function of wave number spectrum, and then is added to global ocean circulation numerical models. The simulated mixed layer depth and SST are much improved [10]. Due to the importance of the upper ocean on climate system, the numerical experiments show that Bv can improve some common problems faced by CGCMs, such as too cold tongue [11]. The purpose of this paper is to add wave-induced mixing to climate model CCSM3 and to improve the model simulation of the SST seasonal cycle in the equatorial eastern Pacific.

The paper is organized as follows: Section 2 gives description of CCSM3 and the wave model, and describes their coupling process; Section 3 presents and discusses the simulation results; And Section 4 is the summary.

2. Model description

We develop an atmosphere-wave-ocean coupled model based on CCSM3 and the wave numerical model, MASNUM (Marine Sciences and Numerical Modeling) spectrum wave model. This section briefly introduces the CGCM and wave model, and then describes their coupling.

2.1 The coupled general circulation model

CCSM3, which was released to the public by the National Center for Atmospheric

Research (NCAR) in June 2004, is one of the state-of-the-art climate models for simulating the earth's climate system. It contains four components of the atmosphere, ocean, sea ice and land surface connected by a coupler that exchanges fluxes and state information among the above four components.

The atmosphere, land surface, sea ice and ocean models in CCSM3 are the Community Atmosphere Model Version 3 (CAM3) [12], the Community Land Model Version 3 (CLM3) [13], the Community Sea-Ice Model Version 5 (CSIM5) [14], and the Parallel Ocean Program Version 1.4.3 (POP1.4.3) [15], respectively. The atmosphere and land surface models have same horizontal resolution, while the sea ice model and ocean model have same horizontal resolution. The POP in CCSM3 employs the Gent and McWilliams isopycnal transport parameterization [16] and the K-Profile Parameterization (KPP) of vertical mixing [17] and an idealized diurnal cycle of solar forcing. Further details of CCSM3 can be found in [8].

In this study, the CCSM3 resolution configuration is referred to as T42_gx1v3. The horizontal resolutions are the T42 spectral truncation for both CAM3 and CLM3 and a nominal 1° for POP and CSIM, with the northern pole displaced into Greenland. The actual ocean and sea-ice horizontal resolutions are 1.125° in longitude and variable from 0.27° (at the equator) to 0.64° (far north-west Pacific) in latitude.

2.2 The wave numerical model

We employ the MASNUM wave number spectrum numerical model [18-20], which has been validated many times by observations and has been used in ocean engineering. In this study, the horizontal resolution is 2° by 2° with the angular resolution is $\Delta\theta = 30^0$ in the wave-number space. In the wave-number space, the wave-number grid is adopted as:

$$K(i) = K_{\min}\exp((i-1)\Delta K), i = 1,......,N+1$$

where

$$K_{\min} = 0.0071, K_{\max} = 0.6894$$

$$\Delta K = \frac{1}{N}\ln\frac{K_{\max}}{K_{\min}}$$

2.3 Coupling

The wave-induced vertical mixing Bv is analytically expressed as a function of the wave number spectrum [10]:

$$Bv = \alpha\iint_{k} E(\vec{k})\exp\{2kz\}d\vec{k}\,\frac{\partial}{\partial z}\left(\iint_{k}\omega^2 E(\vec{k})\exp\{2kz\}d\vec{k}\right)^{1/2} \quad (1)$$

where $E(\vec{k})$ represents the wave number spectrum, ω is the wave angular frequency, k is wave number, and z is the vertical coordinate axis (upward positive with $z=0$ at the surface). α is a constant and is normally set as 1.

We weave the MASNUM wave model into CCSM3 in virtue of the coupler. The wave model gets 10-meter wind from coupler and sends Bv to the coupler every six hours. After obtaining from the coupler, Bv is added to the ocean circulation model of POP through the momentum, temperature and salinity equations as part of the vertical kinematic viscosity or diffusivity [10].

2.4 Numerical experiments

To evaluate the effects of the wave-induced vertical mixing in CCSM3, two numerical experiments are performed. The model used in experiment 1 is original CCSM3, which has been run for three hundred years. The model used in experiment 2 is CCSM3 coupled with the wave model by incorporating wave-induced mixing. The wave-induced mixing is added on January 1 of the first model year. We will use the nomenclature NOWA to refer to the original CCSM3 run and WAVE to refer to the model run with the wave-induced mixing. The effects of the wave-induced mixing on the SST seasonal cycle in the equatorial eastern Pacific are studied by diagnosing the model outputs of the last fifty years (i.e., from model years of 251-300).

3. Result and Analysis

The model-simulated SST seasonal cycle in the equatorial eastern Pacific (110°W-90°W, 5°S-5°N) is shown in Fig. 2. As mentioned above, the results of NOWA show a semi-annual SST cycle with two warm phases in May and December and two cold phases in February and August. The results of WAVE reasonably produce an SST annual cycle with the warm phase in April and the cold phase in August. In other words, the spuriously simulated cold peak in February and warm peak in December by the NOWA disappear in the WAVE. The WAVE-generated warm peak is also shifted from May of the NOWA run to April, consistent with observation (Fig. 1). The correlation calculations between the model results and observation of Levitus data show an improvement in simulating the seasonal cycle from 0.66 for the NOWA to 0.93 for the WAVE. In summary, the incorporation of the wave-induced mixing in CCSM3 can effectively remove the spuriously simulated semi-annual SST cycle in the equatorial eastern Pacific.

A natural question to be asked is: Why does the WAVE experiment remove the spurious semi-annual cycle? To answer this question, we analyze the heat budget in the ocean surface layer. The temperature control equation for the ocean surface layer is as follows:

$$\frac{\partial T}{\partial t} = -u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} - w\frac{\partial T}{\partial z} - \frac{\partial}{\partial z}(A_{hv}\frac{\partial T}{\partial z}) + \frac{F_A}{\rho_0 c_p \Delta z_1} \qquad (2)$$

where T is the ocean surface layer temperature, u, v and w are the surface layer ocean currents in x, y and z directions, A_{hv} is the vertical diffusion coefficient ($A_{hv} = A_{hv} + Bv$, for the WAVE experiment, and Bv is removed in the NOWA experiment. Bv is calculated from wave model through Eq. (1)), Δz_1 is the surface layer depth, ρ_0 is the sea water density, c_p is the specific heat of water, F_A is the net surface heat flux. The term in the left side of Eq. (2) is local change rate of temperature. In the right side of Eq. (2), the first and second terms are the zonal advection and meridional advection; the third term is the vertical advection; the fourth term is the vertical diffusion, including the wave-induced mixing; and the fifth is the net surface heat flux term, including the shortwave radiation penetration. In Eq. (2), we have ignored the horizontal diffusion term which is small.

The difference of each term between the WAVE and NOWA experiments is shown in Fig. 3. The local change rate of SST is in phase with the vertical diffusion term, indicating that the vertical diffusion plays a key role in the improvement of the SST seasonal cycle in the equatorial eastern Pacific by including the wave-induced mixing. Through the physical process of wave-induced mixing, the sea temperature structure, sea surface wind and ocean current system change accordingly [11]. Comparatively, the second large term is the net surface heat flux. In general, the wave-induced mixing cools the ocean surface by bringing subsurface water to the upper layer, so the net heat flux is positive. However, it should be mentioned that sea surface temperature may also increase SST such as too cold tongue area since the sea surface downwelling can appear [11]. The modified meridional advection term also plays some role. The zonal advection plays a constant cooling effect. The vertical advection is quite small, suggesting that the inclusion of the wave-induced mixing does not affect much the contribution of the vertical advection.

Why does the WAVE experiment remove the December warm peak? The rudimentary factor is attributed to the wave-induced mixing. As mentioned above, Bv can also modulate ocean current, temperature structure, and heat flux through SST. Figure 3 shows that the contributions of the vertical mixing, the meridional and zonal advection terms are negative. This indicates that the wave-induced vertical mixing, meridional and zonal advections cool the SST down. That is, the processes of the vertical mixing, meridional and zonal advections play the control role in removing the SST spurious warm peak in December. Figure 3 also suggests that the heat flux and meridional advection difference are responsible for removing the SST spurious cold peak in February.

Although the WAVE experiment removes the spurious semi-annual SST cycle in the equatorial eastern Pacific, its amplitude of the SST annual cycle is weaker than that of observation. From Figures 1 and 2, the observed and simulated (with Bv) SST warm and cold peaks appear in April and August respectively. By considering the wave-induced vertical mixing, the simulated warm peak is lower than that of without wave. Figure 3 suggests that the strong vertical mixing reduces the growth rate of SST. For the cold peak in August, the modulated heat flux and meridional advection by Bv are mainly responsible for the warmer cold peak than that of without Bv. In this way, the wave-induced mixing reduces the amplitude of the SST annual cycle.

Then, we would like to discuss the relationship between the wave-induced mixing and the wind speed in the equatorial eastern Pacific. Figure 4 shows the time series of the wind speed and the wave-induced vertical mixing Bv. Surprisingly, the small value of Bv in summer corresponds to a large wind speed, whereas the large Bv in winter is associated with a small wind speed. This is because Bv is dependent on the surface wave height which is determined by local wind wave and swell. The eastern tropical Pacific area has the highest swell index [21]. The high swell activity mainly comes from high latitude of 40-50°N where the wind is strong in winter and weak in summer. This explains why Bv is small in August and large in December.

In fact, the effect of the wave-induced vertical mixing is not only on the SST, but also on the upper ocean temperature structure, and the impact on the sub-surface can be greater than that on the surface. Figure 5 shows the effect of the wave-induced vertical mixing in the equatorial eastern Pacific (110°W-90°W, 5°S-5°N) during the model years of 251-300. By considering the wave-induced vertical mixing, the maximum difference is 1.0℃ near surface, while more than 5.0℃ at the depth about 60m (Up panel of Fig. 5). From the temperature control equation, the effect of the wave-induced vertical mixing depend on the $\frac{\partial}{\partial z}(Bv\frac{\partial T}{\partial z})$, not only the Bv or the $\frac{\partial T}{\partial z}$. Generally, the largest Bv is at the surface, while the largest $\frac{\partial T}{\partial z}$ normally appears in the thermocline layer. The product of them, as the key factor to influence the temperature evolution, usually reaches its maxima in the sub-surface (Down panel of Fig. 5). The largest $\frac{\partial}{\partial z}(Bv\frac{\partial T}{\partial z})$ locates at the depth about 40m, which is nearly consistent with the changes of the ocean temperature by considering the Bv. It should be pointed out, compared with the sub-surface, the impacting factor of the surface temperature is not just the wave mixing, as well as the heat flux and other factors. The heat flux always has opposite trend with the changes of SST, which can balance the effect of the wave-induced vertical mixing.

4. Summary

A new climate model, which incorporates the MASNUM wave model into CCSM3, has been developed to improve the simulation of the SST seasonal cycle in the equatorial eastern Pacific. The new coupled model successfully removes the spurious semi-annual SST cycle in the equatorial eastern Pacific, a common model problem in most of coupled models. The simulated annual SST cycle is warm in April and cool in August, consistent with observation. The inclusion of the wave-induced vertical mixing has improved the simulated SST correlation with observation from 0.66 to 0.93. Despite the improvement, the new coupled model simulates relatively weak amplitude of the SST annual cycle in the equatorial eastern Pacific. The heat budget analysis shows that the wave-induced mixing plays a key role in the model improvement. This study suggests that the climate model bias of the semi-annual SST cycle in the equatorial eastern Pacific is due to oceanic mixing that is not properly represented. Other challenges such as ENSO periodicity are also improved much by including the surface wave induced vertical mixing Bv, but beyond the scope of the present paper. All above imply that surface wave means a lot in climate system, and it is too important to be ignored in climate models and ocean circulation models.

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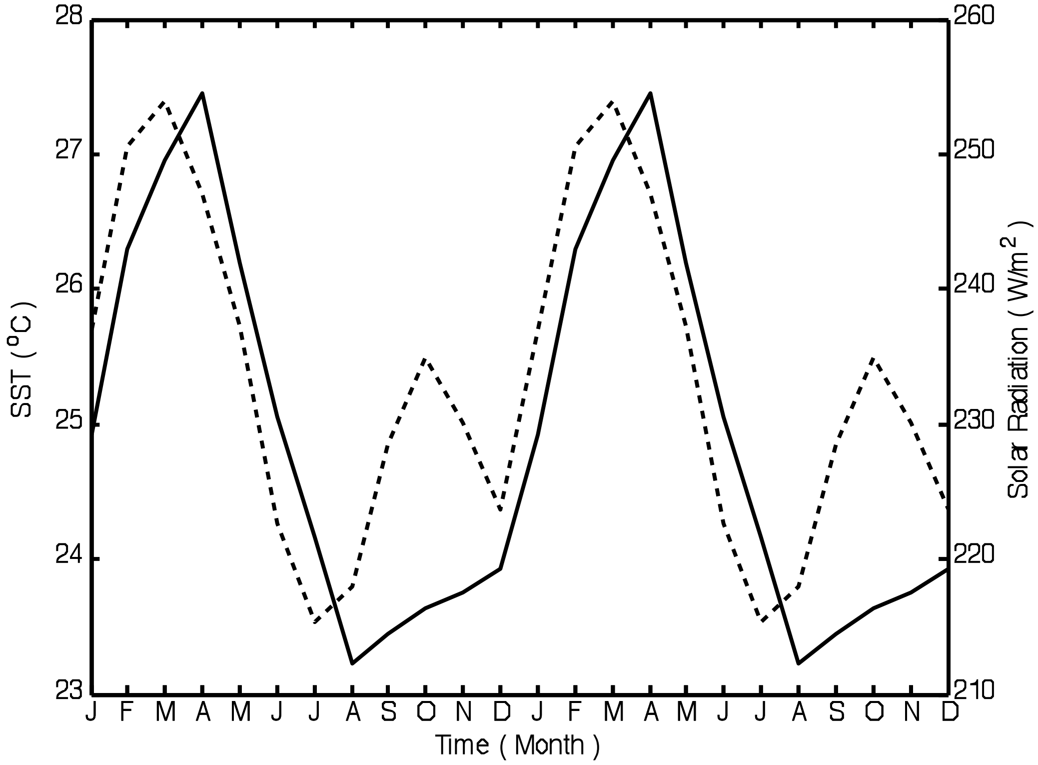

Fig. 1. The seasonal cycle of the SST (solid line, from the Levitus data) and shortwave radiation (dashed line, averaged over 1985-2004) in the equatorial eastern Pacific (110°W-90°W, 5°S-5°N).

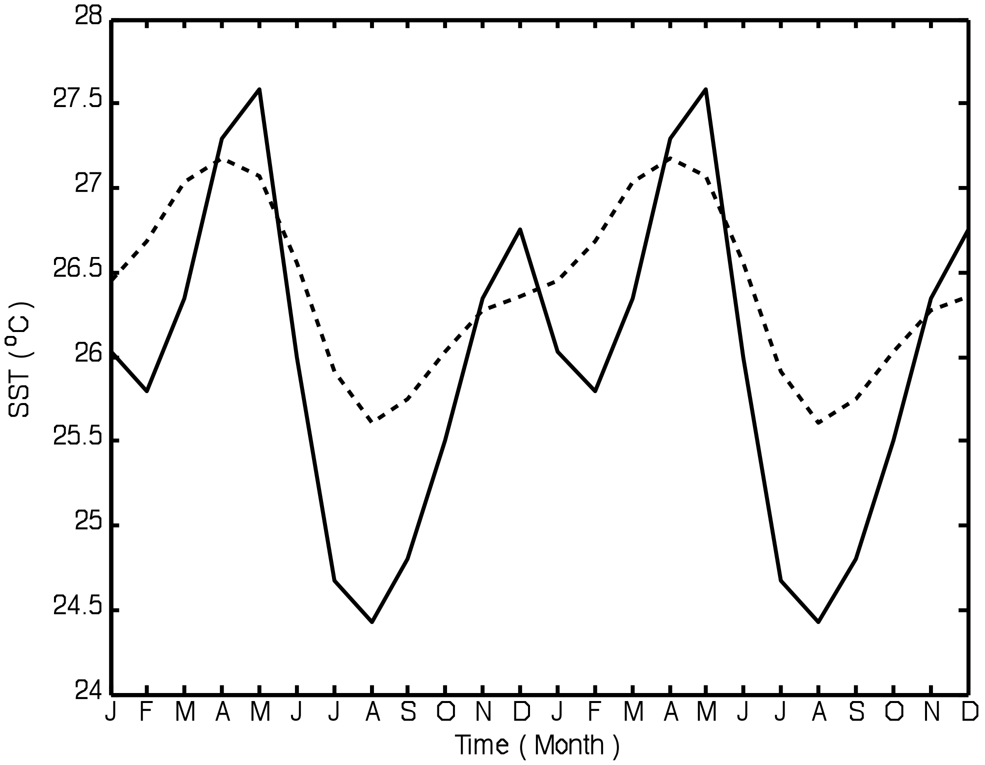

Fig. 2. Simulated SST in the equatorial eastern Pacific (110°W-90°W, 5°S-5°N). The solid line is for the NOWA run and the dashed line represents the WAVE run.

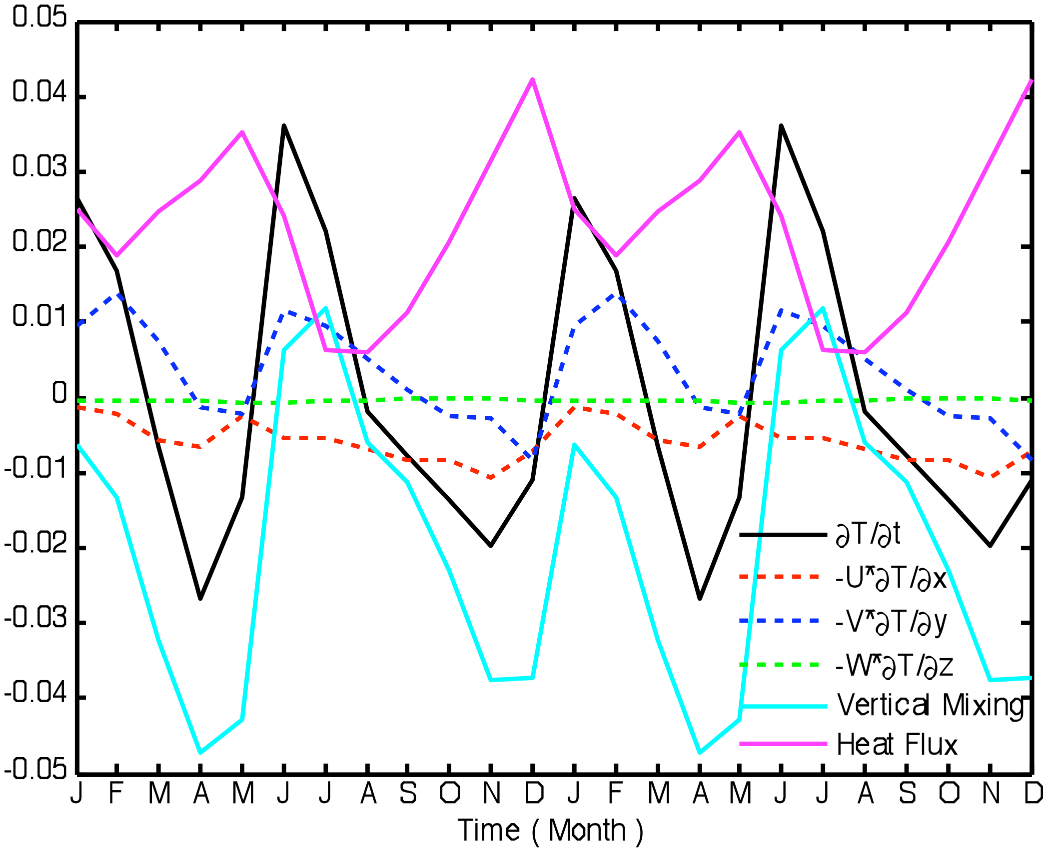

Fig. 3. The difference (WAVE minus NOWA) of various terms in the equation (2). Black line is the local SST change rate (∂T/∂t); Red dashed line is the zonal advection; Blue dashed line is the meridional advection; Green dashed line is the vertical advection; Cyan line is the vertical diffusion; and magenta line is the net surface heat flux.

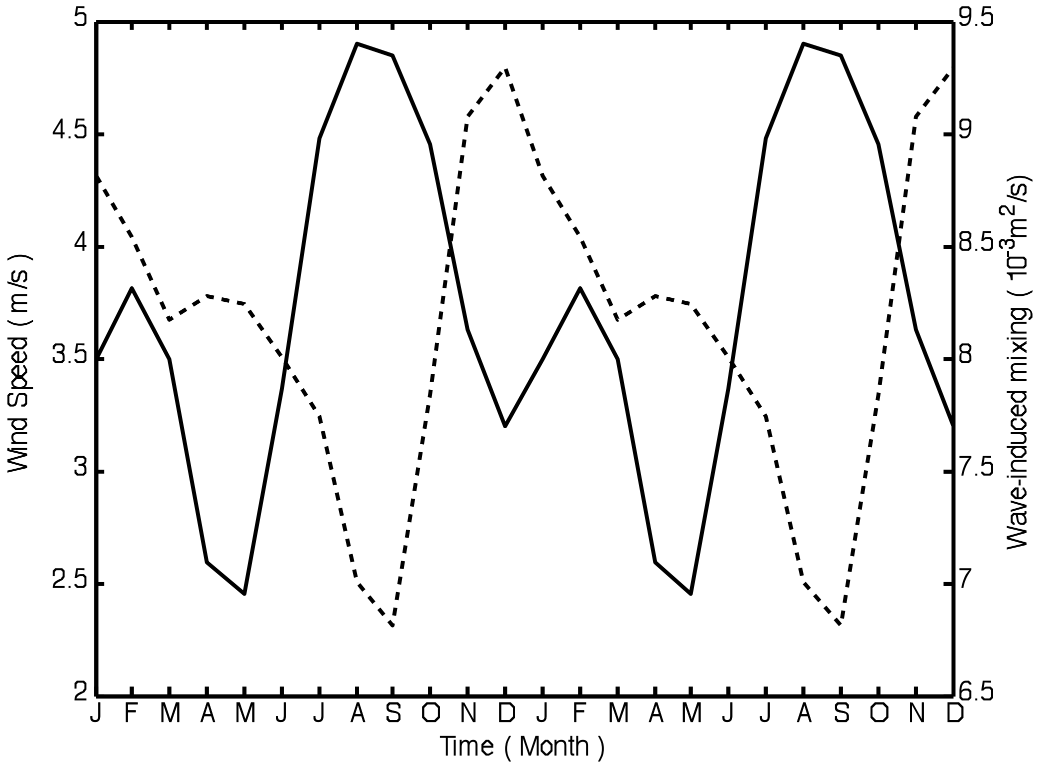

Fig. 4. The seasonal cycle of the surface wind speed and surface layer wave-induced mixing averaged in the equatorial eastern Pacific (110°W-90°W, 5°S-5°N). Solid Line: Wind speed (ms^{-1}); Dashed Line: Wave-induced mixing ($10^{-3}m^2s^{-1}$).

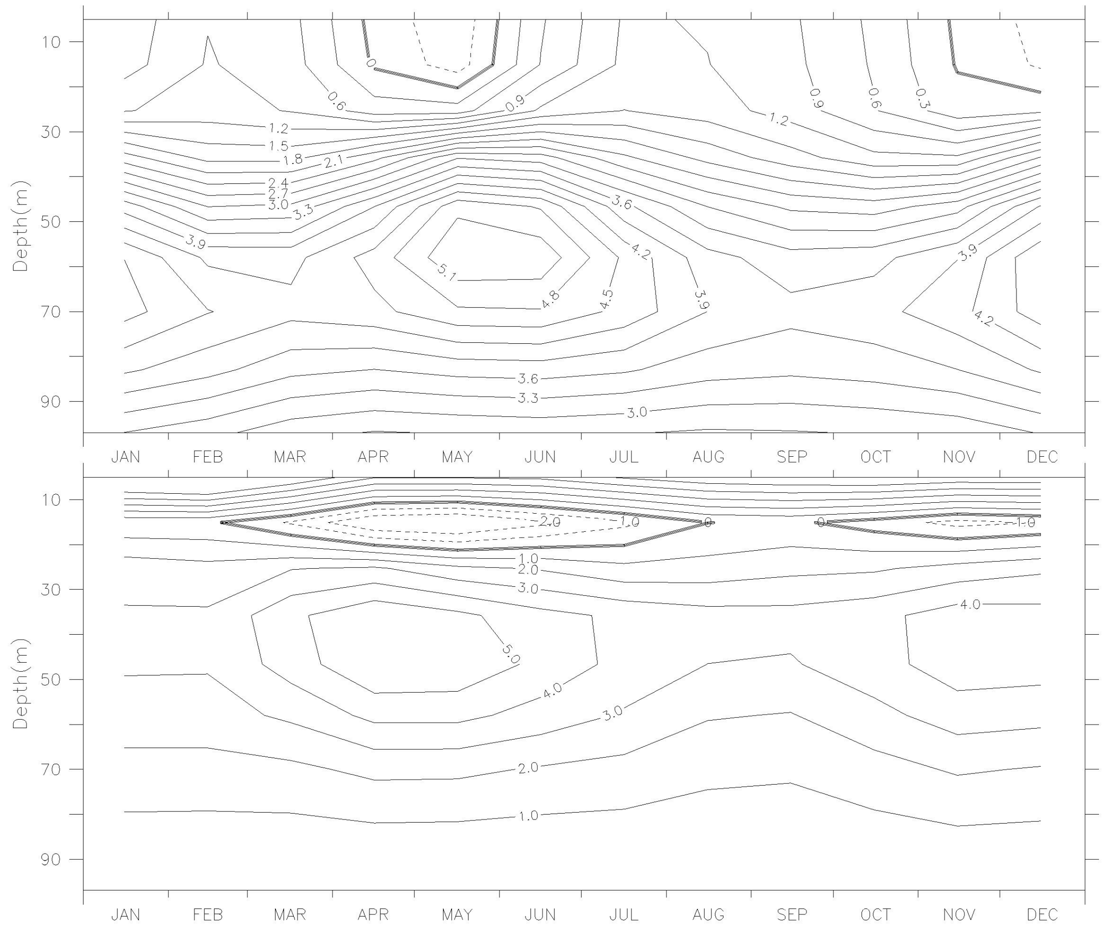

Fig.5. The effect of the wave-induced vertical mixing in the equatorial eastern Pacific (110°W-90°W, 5°S-5°N) during the model years of 251-300 in the upper 100 meters. Up panel: the difference of the temperature simulation of WAVE to NOWA (□); Down panel: the direct effect of the wave-induced vertical mixing, $\frac{\partial}{\partial z}(Bv\frac{\partial T}{\partial z})$ (10^{-6} □s^{-1})